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Abstract

We propose informational spillovers as a new rationale for the use of multiple policy instruments to mitigate a single externality. We investigate the design of a pollution standard when the firms' abatement costs are unknown and emissions are taxed. A firm might abate pollution beyond what is required by the standard by equalizing its marginal abatement costs to the tax rate, thereby revealing information about its abatement cost. We analyze how a regulator can take advantage of this information to design the standard. In a dynamic setting, the regulator relaxes the initial standard in order to induce more information revelation, which would allow her to set a standard closer to the first best in the second period. Updating standards, though, generates a ratchet effect since the low-cost firms might strategically hide their cost by abating no more than required by the standard. We provide conditions for the separating equilibrium to hold when firms act strategically. We illustrate our theoretical results with the case of NO_x regulation in Sweden. We find evidence that the firms that are taxed experience more frequent standard updates.

Keywords: pollution, externalities, asymmetric information, environmental regulation, tax, standards, multiple policies, ratchet effect, nitrogen oxides.

JEL codes: D04, D21, H23, L51, Q48, Q58.

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1 Introduction

The economic literature traditionally argues for the general superiority of market-based policy instruments over command-and-control regulation, primarily because of the relative cost savings expected with market-based approaches. These cost savings arise principally because the latter approaches economize on scarce information about control costs, capitalize on differences in costs among regulated firms, give firms the incentive to minimize costs of current technology, and provide a basis for environmentally sound and cost-effective technological innovation. In practice, the laws pertaining to many major environmental problems, as for instance, clean air, clean water and management of hazardous waste - are typically enacted and managed at all levels of government, implying that many regulations covering the same emission sources overlap and override each other. This is, for instance, the case of climate policy, where all countries and regions that have implemented climate policies seem to rely on several policy instruments (covering the same emission sources) rather than a single one (see e.g., Fankhauser et al. 2010, Levinson 2011 and Novan 2017).

The multiplicity of policy instruments to address a single pollution problem has been justified on several grounds. For instance, some (additional) market failures, regulatory failures or behavioral failures may reduce the economic efficiency of market-based instruments and justify additional policy instruments (see e.g., Bennear and Stavins 2007, Lehmann 2012, Lecuyer and Quirion 2013, Coria et al. 2018). The aim of this paper is not to discuss these justifications, but to introduce and discuss another rationale: the informational value of the policy overlap. In particular, we highlight the informational value of a pollution tax in the design of other environmental regulations when the firm's costs of abating pollution are unknown by the regulatory authorities. We investigate whether and how a tax can help regulators set and update a standard (a cap) on pollutant emissions. Our idea is that the tax rate reveals information about the marginal cost of compliance that can be used to better target the standard to the firm's true cost. Thus, the paper deals with the design of environmental policy with multiple instruments (emission tax and non-tradable caps).

The empirical motivation behind our paper is the regulation of NO_x emissions by stationary pollution sources in Sweden. Since NO_x causes environmental damages at both a national and local level, it is regulated through a combination of a nationally determined emission tax and locally negotiated emission standards which are revised over time. The level of the tax has remained stable since its implementation, although not all pollution sources are taxed. We investigate how taxing emissions has modified emission standards. Does taxing polluters result in more or less stringent standards? How does the standard evolve over time with and without tax? To answer these questions, we develop a theoretical analysis of the design of an emission standard by a welfare-maximizing regulator under asymmetric information about abatement costs, with a tax on emissions which is set exogenously (i.e. out of the control of the regulator). We highlight the informational spillover that the tax induces on the design of the standard over time. We then take advantage of the regulatory heterogeneity between stationary pollution sources in Sweden to investigate the extent to which this informational spillover has been used in the design of NO_x standards at the county level.

To the best of our knowledge, this is the first study investigating the informational value of the use of multiple instruments. Previous studies have analyzed the effectiveness of multiple instruments when there is uncertainty about abatement costs. Building on Weitzman (1974), Roberts and Spence (1976) show, for instance, that a mixed system, involving taxes and quantity regulations (in the form of marketable tradable permits) is preferable to either instrument used separately because such a mix better approximates the shape of the pollution damage function. A similar argument is developed by Mandell (2008) and Caillaud and Demange (2017), who show that, under some conditions, it is more efficient to regulate a part of emissions by a cap-and-trade program and the rest by an emission tax, rather than using a single instrument. Our paper complements this literature by investigating how the information provided by taxes can improve the design of emission standards over time.

Another strand of the literature has taken a mechanism design approach to analyze environmental regulation when abatement costs are unknown by the regulator. Starting with pioneer papers such as Dasgupta, Hammond, and Maskin (1980), Spulber (1988), Lewis (1996) and Duggan and Roberts (2002), this approach has been later applied in specific contexts such as international environmental agreements (Martimort and Sand-Zantman, 2016) or carbon leakage (Ahlvik and Liski, 2017). Those studies rely on direct revelation mechanisms to identify a regulation that induces truthful revelation of abatement costs without restricting the choice of instrument. They end up recommending complex instruments, such as non-linear pollution taxes, that are difficult to implement in practice. In contrast, here we focus on the two most widely used policy instruments to tackle pollution: a tax and a non-tradable cap on emissions. Furthermore, we examine not only how those instruments can induce information revelation but also how the regulator can take advantage of the new information to update the regulation. The dynamic design of regulation with information revelation leads to the well-known ratchet effect that has been studied in contract theory but seldom investigated in the context of environmental policies. Previous theoretical analysis has shown that the ratchet effect precludes information revelation, often leading to pooling and semi-pooling equilibria (Freixas, Guesnerie and Tirole, 1985, Laffont and Tirole, 1988). In our framework, we identify under which conditions the separating equilibrium survives the ratchet effect and how much information is revealed. Furthermore, we show that a higher tax level improves information revelation, and that this effect remains despite the ratchet effect.

The paper is organized as follows. Section 2 motivates our research question based on actual regulation in Sweden. Section 3 introduces the theoretical model. Sections 4 and 5 analyze the choice of emission standard under pooling and separating equilibrium, discussing how the level of the tax can be used to induce revelation of information in a static and dynamic setting, respectively. Section 6 generalizes the results when firms take into account the effect of information revelation on the update of stringency of the regulation. Section 7 illustrates the theoretical analysis in a two-types framework. Section 8 revisits NO_x regulation in Sweden in light of our theoretical analysis. Finally, Section 9 concludes the paper.

2 Empirical Background

For geological reasons, Sweden is particularly vulnerable to acidification, causing negative impacts on lake and forest ecosystems. Consequently, NO_x emissions have been an important environmental policy target in Sweden. Combustion plants are subject to a heavy NO_x national tax and most (but not all) are also subject to individual NO_x emissions standards specified in operating licenses issued case-by-case, either by one of the 21 regional County Administrative Boards, or by one of the five Environmental Courts that cover a geographical area of several counties.[1] Important legislative frameworks that the County Administrative Boards must consider in the determination of NO_x emission standards are some EU directives and the Swedish Environmental Code. If motivated, the regional decision maker can impose more stringent standards than the minimum requirements specified in these directives. These should be determined in line with the Environmental Code which, for example, states that regulations should be based on what is environmentally desirable, technically possible and economically reasonable.

NO_x emissions standards at the production plant level were introduced in the 1980s. There is no legal limit for how long a standard specified in an operating license is valid, though the common practice seemes to be that operating licenses and standards are revised no latter than every tenth year. Firms must, however, apply for a new operating license if they make large changes to the operations (e.g. installing a new boiler or retrofitting a boiler to use a different type of fuel). In addition, there can be appeals that change the original permissions, or postpone conditions for operation. In the application, firms are required to submit information about the operations at the plant and they can propose emission standards based on evidence. However, each County Administrative Board considers whether the suggested emission standards are reasonable. In order not to distort competitiveness, they usually compare emission standards of boilers with similar characteristics in terms of, for example, size and sector classification. If a firm violates the standard specified in the operating license, it risks criminal charges and could face fines to be determined in court.

Regarding the Swedish tax on NO_x emissions from large combustion plants, at the time it was introduced in 1992, close to 25% of the Swedish NO_x emissions came from stationary combustion plants and the tax was seen as a faster and more cost-efficient way of reducing NO_x emissions than the already existing standards. The installation of measuring equipment

[1]After the first of June 2012, only 12 County Administrative Boards, instead of 21, are responsible for issuing the operating licenses.

was judged too costly for smaller plants and the charge therefore was only imposed on larger boilers. In order not to distort competition between larger plants and smaller units not subjected to the tax, a scheme was designed to refund the tax revenues back to the regulated plants in proportion to energy output. Energy output is measured in terms of so-called useful energy, which can be in the form of electricity or heat depending on end-use. Regulated entities belong to the heat and power sector, the pulp and paper industry, the waste incineration sector and the chemical, wood, food and metal industries. Initially the tax only covered boilers and gas turbines with a yearly production of useful energy of at least 50 GWh, but in 1996 the threshold was lowered to 40 GWh and in 1997 further lowered to 25 GWh per year.

We provide evidence that taxed and untaxed boilers are regulated differently by local authorities. We collected information about boiler specific standards for the period 1980-2012 from county authorities (such information is specified in the operating licenses of combustion plants). First, we examine the evolution of standards of both types of boiler (taxed and untaxed), expressed in milligrams of NO_x per MegaJoule (mg/MJ) of useful energy, before and after the tax was introduced. We report the number of boilers and the average standards in Table 1.[2] It turns out that the stringency of standards has increased significantly over time (about 44%, decreasing from an average of 187.05 mg/MJ before the implementation of the charge in 1992 to 104.86 mg/MJ afterward). Moreover, the increased stringency is more pronounced for the group of boilers that are charged (e.g., 48% vs 31% reduction, respectively).

	Number of Boilers	**Standard (mg/MJ) before 1992**	**Standard (mg/MJ) after 1992**
Taxed boilers	516	193.23	101.05
Untaxed boilers	225	165.17	113.90
Total	741	187.05	104.86

Table 1: Average standard before and after the NO_x tax was introduced

We graph the evolution of the average standard between the years 1985 and 2012 for taxed and untaxed boilers in Figure 1.

[2]In total, 819 boilers have been subject to standards. Out of these, 240 have been exempted from the NO_x tax while 579 have been subject to the NO_x tax at least one year since 1992. Standards are, however, expressed in different units. In order to compare their stringency we focus mainly on standards expressed in the same unit: milligrams of NO_x per MegaJoule (mg/MJ) of useful energy. We exclude the 78 boilers whose standards are expressed in other units. We end up with 741 boilers, out of which 516 are taxed.

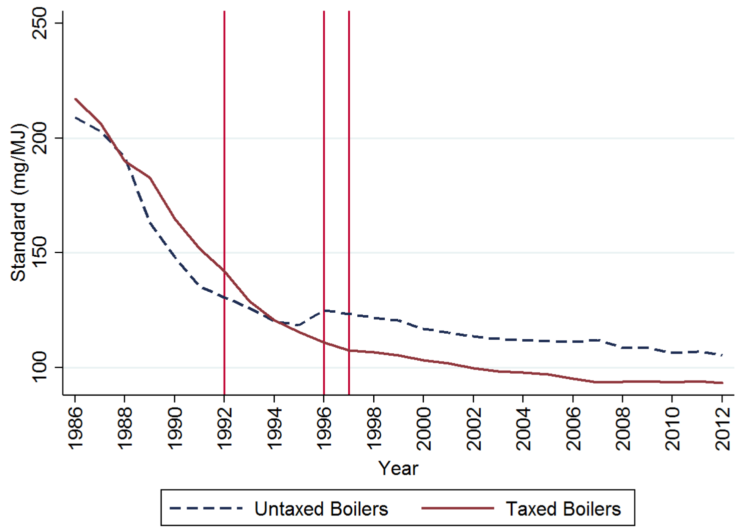

Figure 1: Average Standard by Year

The average standards of the two type of boilers, those that are taxed at some point in time and those that are exempted, follow a similar trend of reduction of the emission standard over time prior to the introduction of the NO_x tax in 1992, 1996 or 1997, depending on the boiler's annual energy use. The two lines diverge just after the tax was introduced, as taxed boilers experienced more stringent standard updates on average.

Second, we examine how standards are updated before and after the tax has been introduced. For a given boiler, we compute the magnitude of the revision $\Delta Standard$ as the difference between the standard that applies to the boiler before and after the revision. The revision strengthens the standard when $\Delta Standard > 0$, while it relaxes it when $\Delta Standard < 0$. In the data, about 20% of the standards of taxed boilers have been revised towards less stringent standards. In Figure 2, we plot the distribution of the magnitude of the standard revisions for the taxed boilers, separating between those revisions that took place before and after the boilers were taxed.[3]

[3]Note that some boilers became subject to the tax in 1992, while other boilers became subject to the tax in 1996 or 1997. Moreover, our data is composed of an unbalanced panel where new boilers appear in the data every year. Thus, the year when a given boiler started to be taxed will depend on the year when the boiler started operating and on the boiler's size.

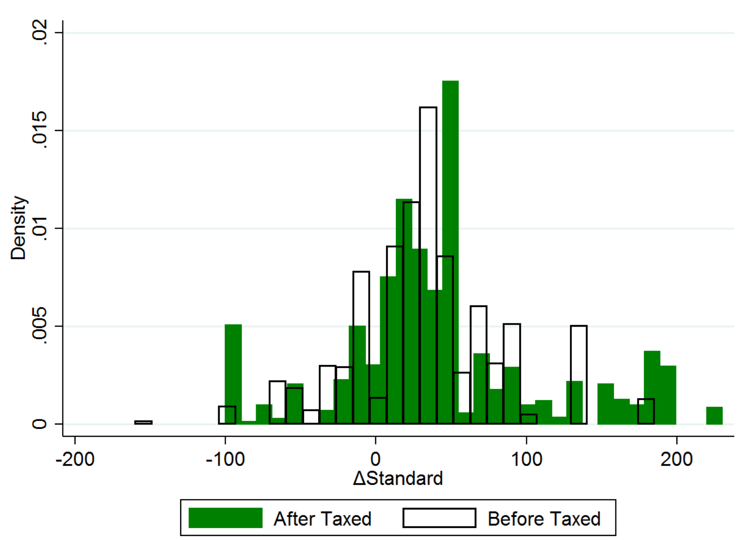

Figure 2: Variations in standard stringency of taxed boilers

The figure suggests a different distribution before and after the introduction of the tax. A two-sample Kolmogorov-Smirnov test allows us to reject the null hypothesis of equality of the distribution. It seems that there is a greater spread in the magnitude of the revision in absolute values when the boilers are taxed, with a higher share of extreme values on both the positive and negative sides. This evidence is consistent with the idea that the information provided by the tax system is used by the local regulators to better tailor the standard. When updating standards, the regulator might take into account whether the boiler over-complies with current standards, and by how much; this would explain the larger variation of the update of stringency of standards for taxed boilers. We explore this explanation in a theoretical framework introduced in the next section.

3 The model

We rely on the textbook model of environmental externality with pollution abatement. Let us assume that a public authority called 'the regulator' (hereafter referred as 'she') is regulating air pollution emitted by a firm through an emission standard. The regulator is a welfare-maximizer: she cares about environmental damage and the cost of controlling pollution. Emissions can be abated by the firm at some cost which is unknown by the regulator. Let q denote pollution abatement. The benefit from reducing pollution by q units is $B(q)$ while the cost is $\theta C(q)$. The parameter θ captures the level of abatement costs. It is called the firm's type and it is exogenously given.[4] It belongs to the range $[\underline{\theta}, \bar{\theta}]$ with $\Delta\theta = \bar{\theta} - \underline{\theta} > 0$. The density and cumulative distribution of the *a priori* beliefs on the distribution of θ over

[4]The model can easily be extended to endogenize θ via the investment in new technologies at expenses of a fixed cost. The same argument would hold as long as the investment is profitable for the firm. If not, the standard might be strengthened further to induce this investment.

the range $[\underline{\theta}, \bar{\theta}]$ are denoted f and F respectively. The benefit function $B(q)$ is increasing and (weakly) concave, reflecting decreasing (or constant) marginal benefit from abating pollution. Similarly, the cost function $C(q)$ is increasing and convex, thereby implying an increasing marginal cost of abating.

The welfare from having a firm of type θ abating q units of polluting emissions is:

$$W(q, \theta) \equiv B(q) - \theta C(q). \tag{1}$$

The first-best abatement level $q^*(\theta)$ maximizes $W(q, \theta)$ with respect to q. It is defined by the following first-order condition:

$$B'(q^*(\theta)) = \theta C'(q^*(\theta)), \tag{2}$$

for every $\theta \in [\underline{\theta}, \bar{\theta}]$.

An emission standard defines a minimal abatement effort denoted s.[5] Assume that pollution is regulated solely through the standard. Under uncertainty about θ, the regulator imposes a standard that maximizes the expected welfare given her beliefs about the firm's type. Let $\hat{\theta} \equiv E_\theta[\theta]$ be the firm's expected type given the regulator's beliefs. The *ex ante* efficient abatement standard $\hat{q}^*$ maximizes the expected welfare

$$E_\theta[W(q, \theta)] = W(q, \hat{\theta}) = B(q) - \hat{\theta} C(q),$$

with respect to q. The first-order condition that defines $q^*(\hat{\theta})$ equalizes the marginal benefit from abatement to the expected marginal cost:

$$B'(q^*(\hat{\theta})) = \hat{\theta} C'(q^*(\hat{\theta})). \tag{3}$$

Consider now a tax per unit of pollution denoted τ. It makes abatement profitable for the firms even in the absence of an emission standard because the firm saves τ each time it reduces emissions by one unit. Therefore, in absence of a standard, the firm chooses the abatement level that minimizes its cost including the tax bill saved, formally $\theta C(q) - \tau q$. Let us denote as $q^\tau(\theta)$ the abatement effort carried out by the firm of type θ. It is defined by the first-order condition that equalizes the marginal abatement cost to the tax rate:

$$\theta C'(q^\tau(\theta)) = \tau. \tag{4}$$

[5] Although the NO_x standard in Sweden is a relative standard determined by units of energy used, we consider an absolute standard (a cap) on emissions in the theoretical model to avoid adding production (energy) as another decision variable. By doing so we ignore output-based strategies to comply with the standard, such as the so-called dilution effect; see e.g. Phaneuf and Requate (2017, Chapter 5). Nevertheless, the main argument holds with relative standards.

Therefore $q^\tau(\theta) = C'^{-1}\left(\frac{\tau}{\theta}\right)$ for every θ. It is increasing with the tax rate τ and decreasing with the type θ.

We analyze the design of a standard s with an exogenous tax on emissions. We assume that the tax does not fully internalize the benefit of abatement. This is to say, the abatement level induced by the tax is sub-optimal regardless of the type: $q^\tau(\theta) < q^*(\theta)$ for every θ.[6]

The *regulation game* is the non-cooperative game aiming at modeling the relationship between the regulator setting the standard and the firm. The tax is exogenous to the two players and common-knowledge. The game is played under adverse selection since the firm observes its type θ before choosing its abatement strategy. The regulator sets the standard s before the firm chooses its abatement effort q. We first consider a static version of the game played only once. We then extend it to two periods to investigate standard revision with information acquisition.

4 The tax as a separating device

4.1 The pooling and separating solutions

We solve the static regulation game by backward induction. Given the abatement standard s, the firm chooses its abatement effort that minimizes its cost subject to complying with the standard. The firm of type θ chooses q that minimizes $\theta C(q) - \tau q$ subject to $q \geq s$. If the constraint is not binding, the tax rate drives the firm's abatement effort and the firm equalizes marginal abatement cost to the tax rate by choosing the abatement level $q^\tau(\theta)$, defined in (4). Otherwise, the firm's abatement effort matches the standard s. Thus, firm θ's best reply to the standard s defines an *incentive-compatibility* (IC) constraint:

$$q(\theta) = \max\{s, q^\tau(\theta)\}. \tag{5}$$

The regulator chooses the standard s that maximizes the expected welfare $E[W(q(\theta), \theta)] = E[B(q(\theta)) - \theta C(q(\theta))]$ subject to the firm's IC constraint (5).

For low tax rates, the tax is not binding and the solution is pooling as all types abate at the standard level. The abatement level $q^\tau(\theta)$ is so low that the IC constraint simplifies to $q(\theta) = s$ for every θ. The standard is set at the first-best level for the mean type $\hat{\theta}$, i.e., $s = q^*(\hat{\theta})$. For higher tax rates and a given standard s, the IC constraint defines a threshold $\tilde{\theta}$ such that $q(\theta) = q^\tau(\theta)$ if $\theta \leq \tilde{\theta}$ and $q(\theta) = s$ if $\theta \geq \tilde{\theta}$. This is to say, firms with a type θ below the threshold abate a level determined by the tax while firms with a type θ above the

[6] This assumption implies that standards are set for all firm types. It avoids considering the case of over-abatement with tax compared to the optimal level. This can easily be justified empirically since most environmental taxes are set below the Pigouvian rate. It is also theoretically grounded because the national tax should reflect only part of the marginal damages due to a boiler's polluting emissions: the part that is not internalized at the county level from the emissions that exit the county's borders.

threshold abate what is required by the standard. The threshold is defined by $q^\tau(\tilde{\theta}) = s$ or, equivalently, by $\tilde{\theta} = \frac{\tau}{C'(s)}$. Hence, the regulator chooses the standard s to maximize:

$$\max_s \int_{\underline{\theta}}^{\tilde{\theta}} W(q^\tau(\theta), \theta) dF(\theta) + \int_{\tilde{\theta}}^{\overline{\theta}} W(s, \theta) dF(\theta) \text{ subject to } q^\tau(\tilde{\theta}) = s.$$

Let us denote the standard that solves this problem as s^s (with an upper-script 's' for static). The first-order condition yields:

$$B'(s^s)[1 - F(\tilde{\theta})] = \int_{\tilde{\theta}}^{\overline{\theta}} \theta dF(\theta) C'(s^s).$$

Using the Bayes rule $f(\theta|\theta \geq \tilde{\theta}) = \dfrac{f(\theta)}{1 - F(\tilde{\theta})}$ leads to

$$B'(s^s) = E[\theta|\theta \geq \tilde{\theta}] C'(s^s), \tag{6}$$

In the separating solution, the standard is chosen such that the marginal benefit of abatement equals the marginal cost in expectation for all types for which the standard is binding, i.e, with a θ higher than $\tilde{\theta}$.[7]

4.2 More information revealed with higher taxes

We now examine how the standard varies with the tax rate.[8] First, the tax rate determines whether the solution is pooling or separating. The solution is separating if the tax rate is higher than a threshold defined by the marginal abatement cost of the lowest-cost type firm $\underline{\theta}$ with the pooling standard $q^*(\hat{\theta})$. That is, if $q^\tau(\underline{\theta}) > q^*(\hat{\theta})$. Using (4), this leads to $\tau > \underline{\theta} C'(q^*(\hat{\theta}))$.

Second, an increase of the tax has two effects on type revelation in the separating solution. The first one is a direct positive effect as higher tax rates induce more revelation of types, since the threshold $\tilde{\theta}$ for which the tax determines abatement increases with τ. Indeed, using the definition of $\tilde{\theta}$, we obtain $\frac{d\tilde{\theta}}{d\tau} = \frac{1}{C'(s)} > 0$, implying that more types are revealed with higher taxes for a given standard s. The second effect is indirect and negative because a higher tax makes the standard more stringent, which reduces $\tilde{\theta}$ for a given tax rate. By differentiating (6) with respect to τ, we observe that

$$\frac{ds}{d\tau} = -\frac{C'(s^s)}{B''(s^s) - E[\theta|\theta \geq \tilde{\theta}] C''(s^s)} > 0$$

[7]Note that our assumption $q^*(\theta) > q^\tau(\theta)$ implies that the standard is binding for some types because $\tilde{\theta} > \underline{\theta}$.

[8]We consider variation of tax rates such that our assumption $q^\tau(\theta) < q^*(\theta)$ for every θ is still valid.

implying that a higher tax increases the standard which, because $\frac{d\tilde{\theta}}{ds} = -\tilde{\theta}\frac{C''(s)}{C'(s)} < 0$, reduces the threshold type $\tilde{\theta}$ and, thus, it reduces revelation of types. We show in Appendix A that the net effect is positive: more types are revealed when the tax increases.

We close this section by summarizing our finding in the following proposition.

Proposition 1 *In the static setting in which firms are regulated both by a standard and a tax, the low cost firms reveal their type by over-complying with the standard. The standard is relaxed and more types are revealed with higher taxes.*

As mentioned in Section 1, previous studies (see e.g., Roberts and Spence (1976) and Pizer (2002)) have shown that using multiple instruments to regulate the same pool of polluters can be welfare enhancing when there is uncertainty about abatement costs. For instance, using an initial distribution of tradable emission permits to set a quantitative target on emissions abatement but allowing for a price cap can be a cost-efficient alternative to either a pure price or quantity system. Proposition 1 is in line with such a result in the sense that a combination of quantity and price control provide firms with greater flexibility to choose the level of emissions abatement closer to the optimal. Nevertheless, the previous studies have ignored another benefit from using multiple instruments: the information revealed about abatement costs. We now investigate how the regulator can make use of this information to improve the regulation. To do that, we need to add a new period into the regulation game. We investigate not only how the information revealed can be used to update the standard but also how it modifies the choice of the initial standard by comparing it to s^s .

5 Information revelation with a myopic firm

5.1 Regulation update

Let us assume now that the regulation game is repeated twice with a discount factor β. The type θ is observed by the firm at the beginning of the game and remains unchanged. Each period t, the regulator sets a standard s_t and the firm chooses the abatement $q_t(\theta)$ for $t = 1, 2$. We assume that the firm is myopic or short-term in its thinking, as it considers only the current abatement costs when picking its abatement strategy. This assumption is relaxed in the next section.

The regulation game with update is a dynamic game under adverse selection. We use the concept of Perfect Bayesian Equilibrium (PBE). The equilibrium strategies are formally described in Appendix B.1. In this section, we solve the game by backward induction. Given the first-period standard s_1, after having observed the firm's abatement strategy in period 1, the regulator designs a new standard s_2. The regulator takes advantage of the information revealed by the firm's abatement decision during the first period to update its beliefs on the firm's type. Given the information obtained, she tailors the standard closer to the firm's expected type.[9] If the firm was over-complying by abating $q^\tau(\theta) > s_1$, the regulator can perfectly infer that its type is θ. She updates the standard to the first-best abatement level $s_2 = q^*(\theta)$. All firm with types lower than the threshold given by:

$$\tau = \tilde{\theta}_1 C'(s_1), \tag{7}$$

are over-complying and, therefore, experience a standard update $s_2 = q^*(\theta)$. If the firm was only abating the level required by the standard s_1, some uncertainty about its type remains. Nevertheless the information on the firm's type becomes more precise because types lower than $\tilde{\theta}_1$ can be excluded. The firm's type should therefore belong to the range $[\tilde{\theta}_1, \bar{\theta}]$. It is distributed according to the conditional cumulative $F(\theta|\theta \geq \tilde{\theta}_1)$.

The updated standard s_2 maximizes the expected welfare given the updated beliefs:

$$E[B(q_2(\theta)) - \theta C(q(\theta))|\theta \geq \tilde{\theta}_1] \text{ subject to } q_2(\theta) = \max\{s_2, q^\tau(\theta)\} \tag{8}$$

The program is similar to that in the static model with the updated beliefs. Let's call $V(s_2, \tilde{\theta}_1)$ the maximal value of (8) given $\tilde{\theta}_1$, i.e.

$$V(s_2, \tilde{\theta}_1) \equiv \max_{s_2} E[W(q_2(\theta), \theta)|\theta \geq \tilde{\theta}_1] \text{ subject to } q_2(\theta) = \max\{s_2, q^\tau(\theta)\}.$$

Let us denote s_2^d the solution to problem (8). In what follows, we discuss the optimal choice of the standards in each period.

5.2 First period's standard

In the first period, the regulator chooses the standard s_1 that maximizes the discounted expected welfare given that the standard will be updated to $s_2 = q^*(\theta)$ if the firm abates more than s_1 and to the standard $s_2 = s_2^d$ if the firm abates s_1. The regulator thus maximizes:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} W(q^\tau(\theta), \theta) dF(\theta) + \int_{\tilde{\theta}_1}^{\bar{\theta}} W(s_1, \theta) dF(\theta) + \beta \left[\int_{\underline{\theta}_1}^{\tilde{\theta}_1} W(q^*(\theta), \theta) dF(\theta) + V(s_2^d, \tilde{\theta}_1) \right] \tag{9}$$

where $\tilde{\theta}_1$ is defined in (7) with $\underline{\theta} < \tilde{\theta}_1 < \bar{\theta}$. The last term in the brackets in (9) is the second-period welfare in expectation. It includes two terms: (i) the first-best welfare $W(q^*(\theta), \theta)$ for firm types $\theta \leq \tilde{\theta}_1$ that revealed their type by over-complying, and (ii) the maximal value of the expected welfare with the revised standard s_2 given the updated beliefs that the firm is of types $\theta \geq \tilde{\theta}_1$.

[9] We focus on the separating solution because no new information is revealed if the solution is pooling. The regulator's beliefs are thus unchanged and so is the standard.

The solution to the problem (9) denoted s_1^d satisfies the following first-order condition:

$$B'(s_1^d) = E[\theta|\theta \geq \tilde{\theta}_1]C'(s_1^d) - \beta \underbrace{\left[W(q^*(\tilde{\theta}_1), \tilde{\theta}_1) - W(q_2(\tilde{\theta}_1), \tilde{\theta}_1)\right]}_{\text{Welfare gain from revealing } \tilde{\theta}_1} f(\tilde{\theta}_1|\theta \geq \tilde{\theta}_1)\frac{d\tilde{\theta}_1}{ds_1}, \quad (10)$$

where $\frac{d\tilde{\theta}_1}{ds_1} = -\tilde{\theta}_1 \frac{C''(s_1^d)}{C'(s_1^d)} < 0$ is found by differentiating (7) and $q_2(\tilde{\theta}_1)$ is the firm $\tilde{\theta}_1$'s abatement level during the second period. The standard s_1^d is such that the marginal benefit of a more stringent standard on the left-hand side of (10) equals the marginal cost on the right-hand side. Likewise for the first-order condition of the static problem in (6), the marginal cost is computed in expectation over all types for which the standard is binding, i.e., all θ higher than $\tilde{\theta}_1$. What is new compared to (6) is the second term on the right-hand side that accounts for the marginal value of the information revealed by the tax. This value is the marginal loss of welfare from not revealing types with a more stringent standard. It is decomposed into three terms. First, $\frac{d\tilde{\theta}_1}{ds_1} < 0$ captures the fact that increasing s_1 decreases the threshold type $\tilde{\theta}_1$, which means that fewer firm's types are revealed. Second, the difference in the brackets $W\left(q^*(\tilde{\theta}_1), \tilde{\theta}_1\right) - W\left(q_2(\tilde{\theta}_1), \tilde{\theta}_1\right)$ is the welfare gain of revealing the marginal type θ_1 (or the welfare loss of not revealing it). Indeed, if $\tilde{\theta}_1$ had been revealed, the standard could be set at the efficient level $q^*(\tilde{\theta}_1)$ in the next period, thereby achieving the maximal welfare $W\left(q^*(\tilde{\theta}_1), \tilde{\theta}_1\right)$. Instead, the welfare level achieved is $W\left(q_2(\tilde{\theta}_1), \tilde{\theta}_1\right)$, where the abatement of the firm of type $\tilde{\theta}_1$ is determined by the second-period standard s_2.[10] Third, this loss is weighted by the regulator's updated beliefs about the share of threshold types $f(\tilde{\theta}_1|\theta \geq \tilde{\theta}_1)$ and discounted with the factor β to be expressed in first-period welfare units.

The welfare gain from revealing $\tilde{\theta}_1$ in (10) is strictly positive, provided that $q^*(\tilde{\theta}_1) \neq q_2(\tilde{\theta}_1)$ and $\beta > 0$. Hence the marginal loss of making the standard more stringent is higher in the dynamic model than in the static one, because the right-hand side of (10) is higher than the right-hand side of (6) for a given standard.[11] Since the left-hand side of both conditions (6) and (10) are the same function of the standard, we have $s_1^d < s^s$. This is to say, the standard is relaxed to acquire information that is used next period.

5.3 Second period's standard

Given s_1 and, therefore the threshold type $\tilde{\theta}_1$, we can now solve the second-period maximization program $V(s_2, \tilde{\theta}_1)$ that defines the second-period standard s_2 if the firm does not over-comply with the standard s_1. $V(s_2, \tilde{\theta}_1)$ is similar to the static problem with updated beliefs $f(\theta|\theta \geq \tilde{\theta}_1)$ on the range of types $[\tilde{\theta}_1, \bar{\theta}]$. In Appendix B.2., we show that the second-

[10] We have $q_2(\tilde{\theta}_1) = q^\tau(\tilde{\theta}_1)$ if the standard is relaxed at $s_2 < s_1$ or $q_2(\tilde{\theta}_1) = s_2$ if it is strengthened at $s_2 > s_1$. The standard update s_2 is examined later on.

[11] Consistently, the first-order (10) boils down to the one of the static model (6) when $\beta = 0$.

period standard denoted s_2^d pools of all types in this range: the threshold type is $\tilde{\theta}_2 = \tilde{\theta}_1$. The first-order condition is then:

$$B'(s_2^d) = E[\theta|\theta \geq \tilde{\theta}_1]C'(s_2^d). \tag{11}$$

The above first-order condition differs from the one that defines s_1^d in (10) by the last term in brackets in (10). It does not show up in (11) because, as the game ends, there is no future gain from revealing types. As the consequence, the standard is strengthened in the second period: $s_2^d > s_1^d$. Updating to a more stringent standard in the second period implies $q_2(\tilde{\theta}_1) = s_2^d$ in (10). Hence, the firm of the threshold type $\tilde{\theta}_1$ abates at the standard level in both periods. Thus, the welfare gain from revealing θ_1 in (10) becomes $W(q^*(\tilde{\theta}_1, \tilde{\theta}_1) - W(s_2^d, \tilde{\theta}_1)$, which corresponds to the difference between the first-best welfare and the welfare with abatement at the standard level s_2^d when the firm is of type $\tilde{\theta}_1$.

Proceeding as in Appendix A, one can show that a higher tax induces more revelation of types, i.e. a lower $\tilde{\theta}_1$, in the dynamic regulation game.

Our results are summarized in the proposition below.

Proposition 2 *In a dynamic setting in which firms are regulated by a standard and a tax, the tax is used to reveal information about the marginal cost of abatement over time. The first-period standard is lower than in the static model to induce more revelation of types, i.e., $s_1^d < s^s$. It is then strengthened to the first-best abatement level if the firm reveals its type by over-complying, i.e., if $q_1(\theta) = q^\tau(\theta) > s_1^d$ then $s_2 = q^*(\theta) > s_1^d$. It is also strengthened if the firm does not overcomply with the standard, i.e., $s_2 = s_2^d > s_1^d$ if $q_1(\theta) = s_1^d$. More revelation of types is achieved with higher taxes.*

Before moving to the analysis of a strategic firm, we briefly discuss how our results would change if the firm's type changes over time. By assuming perfect correlation of type across periods, we assign a maximal value to the information revealed by the environmental tax about the abatement costs in the second period. Full information is revealed if the firm over-complies during the first period, which leads the regulator to implement the first-best. Furthermore, the regulator can exclude a full range of potential types if the firm does not overcomply. In reality, a firm's abatement costs evolve over time due to technological progress and the business environment, which means in our model that the first-period cost type is only partly correlated to the second-period one. Nevertheless, as long as the types are correlated over time, the information revealed in the first period has some value in the second period. Even though the first-best might not be achieved if the firm over-complies, welfare is improved as long as the information about the first-period type allows the regulator to reduce the variance of her beliefs about the second-period type. The standard is probably strengthened but not as much as it would be with perfect correlation. Similarly, when the firm's abatement does not exceed the standard, the full range of potential types excluded in the first period cannot be excluded in the second period. Yet the regulator has more precise information about the firm's type in the second period than she had initially in the first period, which allows her to modify the standard in the second period. Hence, the informational spillovers between policy instruments would remain under imperfect but positive correlation among the firms' abatement costs across time.

6 Information revelation with a strategic firm

Let us assume now that firms are forward looking and strategic. They take into account the impact of their abatement strategy in the first period on the second period standard. The revision of the standard leads to the well-known *ratchet effect* in the separating equilibrium of the dynamic regulation game. As the regulator makes the standard more stringent for firms revealing their low-cost type, it induces them to hide their type by abating only the level required by the standard.

Two behaviors might prevent the revelation of types. First, the firm of type θ might hide its cost by abating at the level of the standard s_1 instead of its cost-minimizing abatement level $q^\tau(\theta) > s_1$. Doing so, the firm increases its cost in the first period. However, this extra cost can be more than offset by the future gain from a lower standard updating, as the firm the will be required to abate s_2 instead of $q^*(\theta)$. Second, firm θ might mimic a higher-cost type $\theta' > \theta$ by picking the abatement strategy $q^\tau(\theta') > s_1$ to avoid a more stringent standard update in the future, i.e. $s_2 = q^*(\theta')$ instead of $s_2 = q^*(\theta)$ with $q^*(\theta') < q^*(\theta)$. We examine these two types of opportunistic behavior separately.[12] They define two dynamic incentive-compatibility constraints ensuring truthful revelation of types with strategic firms.

Firm θ reveals its type by abating more than the standard, if the following dynamic incentive-compatible constraint holds:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \beta[\theta C(q^*(\theta)) - \tau q^*(\theta)] \leq \theta C(s_1) - \tau s_1 + \beta[\theta C(q^\tau(\theta)) - \tau q^\tau(\theta)]. \quad (12)$$

The discounted cost if the type is revealed on the left-hand side of (12) should be not be higher than if it is hidden in the right-hand side. The firm has to balance the current extra cost of abating s_1 instead of its cost-minimization level $q^\tau(\theta)$ (first two terms on each side of the inequality), with the future benefit of being able to minimize cost by abating $q^\tau(\theta)$ instead of updated standard $q^*(\theta)$ (terms in brackets on the two sides of the inequality), discounted in present value.[13]

[12] Note that a firm would never mimic a lower type because it would imply abating more both periods.

[13] Note that if the game lasted more than two periods (i.e. the standard was updated several times), the firm might hide its type again in the second period to avoid the standard being updated to $q^*(\theta)$ later on. This reduces the benefit from hiding type in the future and, therefore, relaxes the dynamic-incentive compatible constraint (12). In this sense, we are conservative about the conditions for information revelation when we limit our analysis to only two periods. If the separation equilibrium can be implemented in a two-period game, it can also be implemented if the game continues for more periods.

It is possible to show that the dynamic incentive-compatible constraint for hiding the type is binding for any standard. Indeed, substituting $s_1 = q^\tau(\tilde{\theta}_1)$ into (12) shows that this inequality does not hold. By continuity, it does not hold either for types close to $\tilde{\theta}_1$. Hence, strategic firms undermine information revelation. However, if the cost difference between revealing and hiding type is increasing with θ, condition (12) might hold for the lowest cost-types θ. In Appendix C.1 we define conditions for which this is indeed the case. It basically requires that the cost function $C(q)$ is not too convex and/or the discount factor β is not too high. Under Assumption 1 in Appendix C.1, we can define $\dot{\theta}$ as the threshold such that (12) holds for all $\theta < \dot{\theta}$. Formally, $\dot{\theta}$ is defined by binding the dynamic IC constraint (12), i.e.,

$$\dot{\theta}C(q^\tau(\dot{\theta}))-\tau q^\tau(\dot{\theta})+\beta[\dot{\theta}C(q^*(\dot{\theta}))-\tau q^*(\dot{\theta})] = \dot{\theta}C(q^\tau(\tilde{\theta}_1))-\tau q^\tau(\tilde{\theta}_1)+\beta[\dot{\theta}C(q^\tau(\dot{\theta}))-\tau q^\tau(\dot{\theta})]. \quad (13)$$

Second, firm θ does not mimic another type θ' by abating $q^\tau(\theta') > s_1$ if the following dynamic-incentive constraint holds:

$$\theta C(q^\tau(\theta))-\tau q^\tau(\theta)+\beta[\theta C(q^*(\theta))-\tau q^*(\theta)] \leq \theta C(q^\tau(\theta'))-\tau q^\tau(\theta')+\beta[\theta C(q^*(\theta'))-\tau q^*(\theta')]. \quad (14)$$

Firm θ might be tempted to abate less that its cost-minimizing level $q^\tau(\theta)$ because, due to the convexity of the cost function $C(q)$, the present extra cost $\theta C(q^\tau(\theta')) - \tau q^\tau(\theta') - [\theta C(q^\tau(\theta)) - \tau q^\tau(\theta)]$ is more than offset by the future cost saved $\theta C(q^*(\theta)) - \tau q^*(\theta) - [\theta C(q^*(\theta')) - \tau q^*(\theta')]$. Let us denote by x the best type to mimic (if any). The type x is formally defined by:

$$x = \arg\min_{\theta' > \dot{\theta}} \{\theta C(q^\tau(\theta')) - \tau q^\tau(\theta') + \beta[\theta C(q^*(\theta')) - \tau q^*(\theta')]\}.$$

We denote by $\tilde{\beta}(\theta)$ the highest discount rate such that the dynamic incentive-compatibility constraint holds for type θ:

$$\tilde{\beta}(\theta) \equiv \frac{\theta C(q^\tau(x)) - \tau q^\tau(x) - [\theta C(q^\tau(\theta) - \tau q^\tau(\theta)]}{\theta C(q^*(\theta) - \tau q^*(\theta) - [\theta C(q^*(x) - \tau q^*(x)]}, \quad (15)$$

In Appendix C.2, we show that $\frac{d\tilde{\beta}(\theta)}{d\tau} > 0$ for every $\theta > \dot{\theta}$ and $\frac{d\dot{\theta}}{d\tau} > 0$, which leads to the following proposition.

Proposition 3 *In the dynamic regulation game with a strategic firm, a higher tax improves information revelation by increasing the threshold type $\dot{\theta}$ and by increasing the maximal discount rate $\tilde{\beta}(\theta)$ for every θ at which the firm does not have incentive to reveal its type.*

Under Assumption 1, the separating solution is still feasible when the firm acts strategically when choosing its level of abatement. Proposition 3 states that a higher tax makes the separating solution more likely because it relaxes the dynamic-incentive constraint in (14). A higher tax makes mimicking other types less attractive and, therefore, (14) holds for lower discount rates. Furthermore, in line with Propositions 1 and 2, Proposition 3 establishes that a higher tax rate reveals more types in the separating solution by increasing the threshold type $\dot{\theta}$. The latter result relies on the same intuition: a higher tax favors over-compliance despite the fact that the standard becomes more stringent. As the tax increases, hiding cost by not over-complying is not profitable anymore for a larger range of firm types.

7 Illustration with two types

The choice between a pooling or a separating solution can be illustrated in the two-types case. Let us assume that θ can only take two values: $\bar{\theta}$ (high) and $\underline{\theta}$ (low). The regulator assigns a probability ν that $\theta = \bar{\theta}$. For simplicity, let us denote $q(\underline{\theta})$ and $q(\bar{\theta})$ by $\underline{q}$ and $\bar{q}$ respectively. We graph the marginal abatement costs as well as the marginal benefit of reducing pollution in Figure 3. The *ex post* efficient abatement levels $\overline{q}^*$ and $\underline{q}^*$ can be found

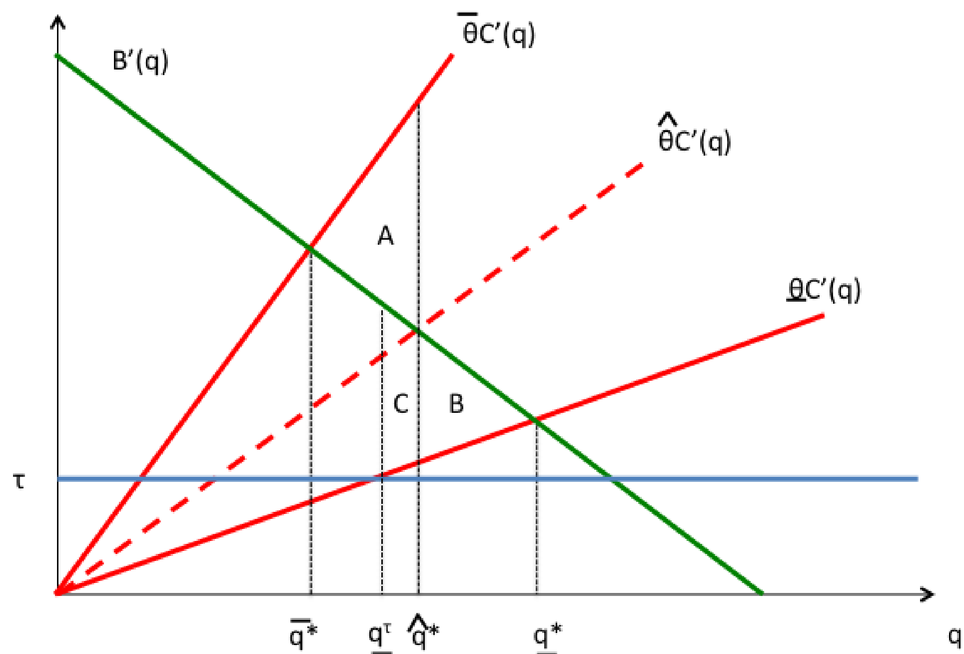

Figure 3: Welfare loss with the pooling and separating solutions.

where the marginal abatement cost curve crosses the marginal benefit curve for each type of firm. Similarly, the pooling abatement standard $\hat{q}^*$ is such that the marginal abatement cost curve for the expected type $\hat{\theta}$ (in dotted line) crosses the marginal benefit curve. The tax rate is represented by the horizontal line τ. The abatement level with tax for the low-cost firm $\underline{q}^\tau$ can be found where this horizontal line crosses the marginal abatement cost for the low-cost firm $\underline{\theta}C'(q)$.

The loss of welfare under the pooling solution is represented by the areas A and B. If the firm's cost type is $\bar{\theta}$, the standard $\hat{q}^*$ induces too much pollution reduction $\hat{q}^* > \overline{q}^*$. The cost of reducing emissions is higher than the benefit for all reduction units between $\overline{q}^*$ and $\hat{q}^*$. The loss of welfare is thus the difference between the marginal cost and the marginal benefit of abatement given by the area A. Symmetrically, if the firm's cost-type is $\underline{\theta}$, more pollution should be abated than prescribed by the standard. The benefit from reducing pollution is higher than the cost for all abatement levels from $\hat{q}^*$ to $\underline{q}^*$. The loss of welfare is thus the difference between the marginal benefit and the marginal cost of abating pollution given by the area B. Since the regulator assigns probabilities ν and $1-\nu$ that the firm is of type $\underline{\theta}$ and $\overline{\theta}$, the expected loss of welfare is $\nu A + (1-\nu)B$. Under the separating solution, the standard corresponds to $\overline{q}^*$. Thus, the standard implements the efficient abatement level if the firm's type is $\overline{\theta}$ and, hence, there is no loss of welfare in this case. If the firm's type is $\underline{\theta}$, its abatement is given by $\underline{q}^\tau$. However, $\underline{q}^\tau$ is lower than the efficient abatement level $\underline{q}^*$, and thus the loss of welfare under the separating solution is represented by the area $C+B$. Since the firm is of the low cost-type with probability ν, the expected loss of welfare is $\nu(C+B)$.

For a low tax rate such that the standard $\overline{q}^*$ is close to the abatement level $\underline{q}^\tau$, the expected loss of welfare with the separating solution $\nu(C+B)$ might be greater than the loss of welfare under the pooling solution $\nu A + (1-\nu)B$.[14] In this case, pooling dominates separation of types. As the tax rate increases, the horizontal line moves up and, at some point, the ranking is reversed.[15] It dominates as well as τ increases further. When τ is such that $\underline{q}^\tau = \underline{q}^*$, the separating solution implements the first-best abatement levels in the two-types case.

Let us denote τ_s as the tax rate such that expected welfare is equal under the screening and separating solutions:

$$\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) = W(\hat{q}^*, \hat{\theta}). \tag{16}$$

We show in Appendix D.2 that the pooling solution dominates when the tax rate is lower than τ_s, while the screening dominates when it is above.

In the two-types case, the regulator can perfectly infer the firm's type with the separating solution. If the firm abates more than required by the standard, the regulator knows that the firm is of type $\underline{\theta}$. If it does not exceed the standard, the firm is of type $\overline{\theta}$. Therefore, in both cases, the regulator can implement the ex-post efficient abatement levels. The standard is tightened to the efficient level for the low-cost type $\underline{q}^*$ when the firm was abating more than required by the standard. If not, the standard is left unchanged at the efficient level for the

[14] This is particularly the case when the low cost-type is more likely so that ν is high.

[15] In particular, the separating solution dominates when the rate τ is such that $\underline{q}^\tau = \hat{q}^*$. If the firm is of type $\underline{\theta}$, the loss of welfare is the same under separating and pooling (i.e. area B in Figure 1). If it is of type $\overline{\theta}$, there is no loss of welfare under separating but a loss corresponding to area A under pooling. Hence the separating solution dominates.

high-cost type $\overline{q}^*$.

The information acquisition makes the separating solution more attractive for the regulator in the dynamic setting. Indeed, the expected discounted welfare with the screening solution is $\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu)W(\overline{q}^*, \overline{\theta}) + \beta E_\theta[W(q^*(\theta), \theta)]$. This has to be compared with the expected discounted welfare with pooling $(1+\beta)W(\hat{q}^*, \hat{\theta})$. The minimal tax rate τ_d with screening dominates pooling; this is implicitly defined by equalizing the expected discounted welfare from the two solutions:

$$\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu)W(\overline{q}^*, \overline{\theta}) = W(\hat{q}, \hat{\theta}) - \beta \left[E_\theta[W(q^*(\theta), \theta)] - W(\hat{q}^*, \hat{\theta}) \right]. \tag{17}$$

Since the last term in brackets is positive, the right-hand term in (17) is lower than the right-hand term of (16), while the left-hand terms are the same. Furthermore, the left-hand terms are increasing with τ while the right-hand terms do not vary with τ. Therefore $\tau_d < \tau_s$. Put differently, for tax rates in-between τ_d and τ_s, the standard update makes the screening solution more attractive through the revelation of types.[16]

Regarding strategic firms, the trade-off facing a low-type firm when decided whether to reveal its type is illustrated in the two-types case in Figure 4 below.

[16]Interestingly, welfare increases with the tax rate in the separating solution. Differentiating the expected welfare under the separating solution (the left-hand side of (16)) with respect to τ leads to $\nu W_q(\underline{q}^\tau, \underline{\theta}) \frac{d\underline{q}^\tau}{d\tau}$ which is strictly positive because (i) abatement $\underline{q}^\tau$ increases with the tax rate (last term positive), (ii) welfare increase with abatement for $\underline{q}^\tau \leq \underline{q}^*$ and, therefore, $W_q(\underline{q}^\tau, \underline{\theta}) > 0$. Intuitively, a higher tax moves the abatement level of the low-cost firm closer to the first-best.

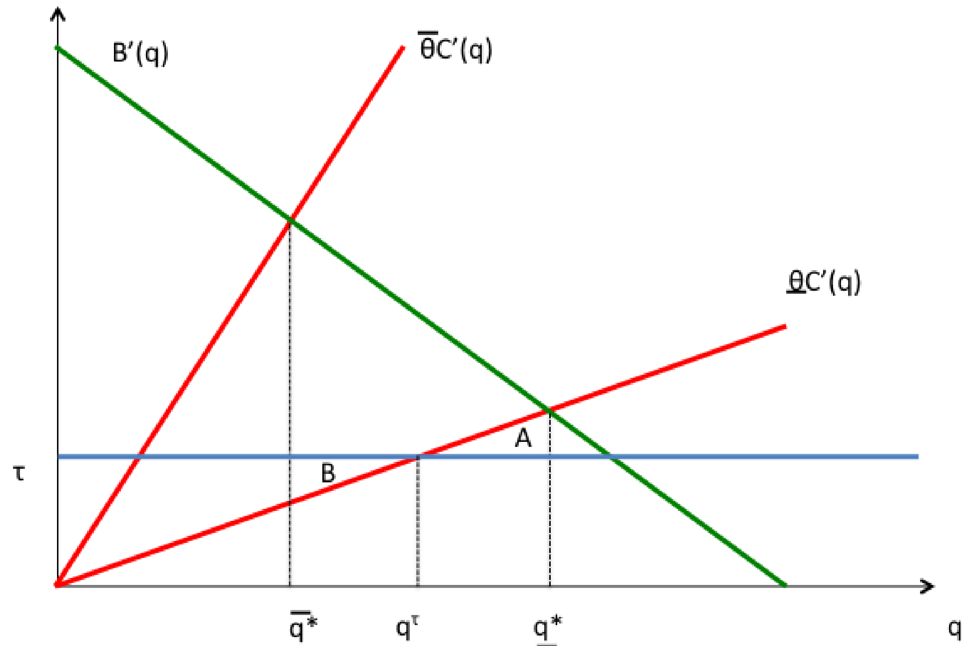

Figure 4: Loss if the low-cost firm reveals or hides its cost.

For a tax rate graphed by the horizontal line τ, the cost of revealing type or hiding it is represented by areas A and B respectively. If the firm reveals its type, the standard is revised to $\underline{q}^*$ in the next period, which forces the firm to abate $\underline{q}^* - \underline{q}^\tau$ more units. The cost of each of those abatement units is the difference between the marginal cost and the tax rate: that difference is equal to the area A. This extra cost in period two is valued at βA in period 1. If the firm hides its type by abating less than it otherwise would have at the standard $\overline{q}^*$, it loses the difference between the tax rate and the marginal cost for all abatement units between standard $\overline{q}^*$ and its best choice $\underline{q}^\tau$; that difference is area B. The horizontal line moves upward as τ increases and, therefore, B expends while A shirks. At some point βA becomes smaller than B: the cost of revealing the type becomes lower than the cost of hiding it.

8 Empirical Analysis

We now look more closely at the data collected on NO_x regulation in Sweden in light of the theoretical analysis. To be precise, we investigate two theoretical predictions of our model: (i) boilers that are taxed experience more updating of their standards (more frequent and greater magnitude) compared to boilers that are not, (ii) the standards for the taxed boilers become more stringent for over-complying boilers compared to boilers that emit no more than the standard. The first prediction is analyzed by comparing taxed and untaxed boilers while the second is analyzed by invesigating the determinants of the magnitude of the update of the standards for taxed boilers.

8.1 Impact of the NO_x tax on emission standard updates

Since standards are examined unevenly across time, we use two statistics to measure the standard update: the frequency and the magnitude of the revisions. Table 2 presents summary statistics of the revisions of stringency of untaxed boilers (223 boilers in the sample)[17] and taxed boilers (516 boilers in the sample). On average, there is a statistically larger fraction of revisions for taxed boilers than for untaxed boilers (e.g., 60% vs 41%). Moreover, the magnitude of the revision Δ Standard is statistically larger for taxed boilers. Furthermore, the number of years between revisions is statistically lower for taxed boilers.

	Untaxed	**Taxed**	**Diff.**
# Boilers	223	516	—
# Standards	324	901	—
Standards revised (%)	41	60	***
Δ Standard (mg/MJ)	23.63	38.87	***
Years between revisions	6.02	6.69	***
* $p < 0.1$,** $p < 0.05$ and *** $p < 0.01$			

Table 2: Statistics on standards update

We first evaluate the effect of the NO_x tax on the probability of standard revision and on the magnitude of the revision. The outcomes variables correspond to P_{ijt} and $\Delta Standard_{ijt}$, where P_{ijt} takes a value equal to one if the standard that applied to boiler i located at county j was revised at time t, and zero otherwise. As described before, $\Delta Standard_{ijt}$ corresponds to the difference between the standard that applies to boiler i (located at county j) at time $t-1$ and the standard that applies to boiler i at time t.

The outcome variables P_{ijt} and Δ Standard_{ijt} are regressed as a function of the NO_x tax regulation, measured by the dummy variable Tax_{ijt-1} that takes a value equal to one if boiler i located at county j is subject to the NO_x tax at time $t-1$ and zero otherwise. We should expect the probability of standard revision and the stringency of the revision to depend on the length of time that has elapsed since the previous revision. We proxy for this by the log of the number of years that have elapsed since the boiler was regulated by the last time, denoted as $\Delta \log \text{Years}_{ijt}$. For boilers whose standard has never been revised, the

[17] We have excluded outliers.

variable corresponds to the log of the number of years that have elapsed since the boiler was assigned the first standard. For those boilers whose standard has been revised, the variable corresponds to the log of the number of years that have elapsed between standard revisions. We use a logarithmic transformation because the number of years that have elapsed since the boiler was last regulated is a highly skewed variable.

Additional controls include a vector Z of L boiler and firm characteristics (for instance, industrial sector and boiler size). Moreover ζ_j are county fixed effects that account for non-observable characteristics of the county that can affect the stringency of the standards, η_t are yearly fixed effects to account for any variation in the outcome that occurs over time and that is not attributed to the other explanatory variables, and ε_{ijt} is the error term.

$$P_{ijt} = \alpha + \beta \mathrm{Tax}_{ijt-1} + \gamma \Delta \log \mathrm{Years}_{ijt} + \sum_{l=1}^{L} \kappa_l Z_{il} + \zeta_j + \eta_t + \varepsilon_{ijt}, \tag{18}$$

$$\Delta \mathrm{Standard}_{ijt} = \alpha + \beta \mathrm{Tax}_{ijt-1} + \delta \Delta \log \mathrm{Years}_{ijt} + \sum_{l=1}^{L} \kappa_l Z_{il} + \zeta_j + \eta_t + \varepsilon_{ijt}, \tag{19}$$

We estimate equations (18) and (19) with robust standard errors clustered at the boiler level to account for the potential correlation of the standard designed for a given boiler.

The data is an unbalanced pooled cross-section over time panel of boilers, where boilers are observed every year from the year when they are assigned the first standard. In our sample, each boiler has received (on average) 1.92 standards, and 427 out of 739 boilers have been assigned only one standard during the whole sampled period. Those boilers that have received more than one standard have received (on average) 2.7 standards, and the average number of years between revisions is 6.1 years.

Regarding the sources of data, information about standards over the period 1980-2012 specified in the operating licenses of combustion plants was obtained from county authorities. Information on NO_x emissions over the period 1992-2012 comes from the Swedish NO_x database, which is a panel covering all boilers monitored under the tax system. The NO_x database also includes information on boiler capacity and industrial sector.

See Table 3 for a description of the variables.

Variable	Description	N	Mean	Std.Dev.	Min	Max
Standard	mg/NO_x	11477	110.77	50.22	21.90	300
Tax	1 if subject to NO_x tax; 0 otherwise	11477	0.70	0.45	0	1
# Standards	# of Standards	11477	1.92	1.09	1	7
Standard Revised	(%)	11477	0.54	0.50	0	1
ΔStandard	Current − Previous standard	3757	35.68	60.21	-160	230
logΔYears	log of # years last regulated	10585	1.65	0.84	0	3.33
Boiler/Firm Characteristics						
Waste	1 if waste; 0 otherwise	11477	0.11	0.31	0	1
Food	1 if food; 0 otherwise	11477	0.07	0.25	0	1
Heat and Power	1 if heat and power; 0 otherwise	11477	0.68	0.47	0	1
Pulp and Paper	1 if pulp and paper ; 0 otherwise	11477	0.06	0.24	0	1
Metal	1 if metal; 0 otherwise	11477	0.015	0.12	0	1
Chemicals	1 if chemicals; 0 otherwise	11477	0.025	0.16	0	1
Wood	1 if wood ; 0 otherwise	11477	0.04	0.20	0	1
Boiler Size	Installed boiler effect in MW	10895	55.14	94.51	1.3	825

Table 3: Summary Statistics

From Table 3, we observe that 70% of the boilers have been taxed at some point in time, and that the majority of the boilers in the dataset belong to the heat and power sector. Moreover, there is large variation among standards both in stringency and frequency of revision. Such variation reflects differences in boiler size, technology availability, and industrial sector, among others.

Table 4 presents the results of the regression model specified in equation (18): see cols (1)-(3). In col (1) we control for sectorial fixed effects. In col (2) we control also for county fixed effects, while in col (3) we control for sectorial, county and yearly fixed effects. Moreover, cols (4)-(6) present the results of the regression model specified in equation (19), where - again- in col (4) we only control for sectorial fixed effects, in col (5) we control for sectorial and county fixed effects, and in col (6) we control for sectorial, county and yearly fixed effects.

In cols (1) and (3), a negative sign of the coefficient indicates that the determinant reduces the probability of standard revision. We observe that taxed boilers have indeed a statistically significant higher probability of being revised. In the specifications in cols (1) and (2), being taxed increases the probability of standard revision by about 20%. In specification (3), the effect is even larger as the probability of revisions for taxed boilers is about 30% higher than that of tax-free boilers.

The time that has elapsed since the boiler was last regulated also increases the probability of revisions in all specifications. Interestingly, the results in cols (1) and (2) show that the standards of larger boilers are also more likely to be revised.

Regarding cols (4)-(6), in col (3) the results do not support the hypothesis that the stringency of the standard revisions is larger for boilers that are taxed. The results show, however, that the longer the time that elapses between standard revisions, the greater is the magnitude of the revision. Moreover, the magnitude of the revisions seem to be larger for larger boilers.

Hence, we can conclude that the results provide empirical support to our hypothesis that the standards of taxed boilers are revised more often, yet it is unclear whether the stringency of the revisions is greater for taxed boilers. A potential explanation is the existence of spillover effects between taxed and untaxed boilers. After increasing the stringency of standards for taxed boilers, the regulator might require boilers that are not taxed to implement similar technologies and management practices for reducing pollution. This argument is consistent with the trends observed in Figure 1, where both taxed and untaxed boilers have reduced their emissions significantly over time. Moreover, even if the magnitude of the revisions is not affected by the NO_x tax, the fact that the standards of taxed boilers are revised more often should, over time, also increase the overall stringency of the standards, since more frequent increases in the standard stringency for taxed boilers should lead to greater increases in the standard stringency for untaxed boilers when these are revised.

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	P_{ijt}			$\Delta Standard_{ijt}$		
NO_x Tax_{t-1}	0.19^{***}	0.19^{***}	0.29^{***}	3.50	-2.10	-0.52
Log ΔYears_t	0.17^{***}	0.19^{***}	0.28^{***}	4.90^{***}	3.78^{**}	8.76^{**}
Size_{ijt}	0.0006^{***}	0.0004^{***}	0.0002	0.062^{*}	0.063^{**}	0.050^{*}
FE Sector	YES	YES	YES	YES	YES	YES
FE County	NO	YES	YES	NO	YES	YES
FE Year	NO	NO	YES	NO	NO	YES
#Obs	9981	9981	9732	3490	3490	3490
#Boilers	681	673	673	301	301	301
Pseudo R^2/R^2	0.023	0.037	0.068	0.04	0.22	0.24
* $p < 0.1$, ** $p < 0.05$ and *** $p < 0.01$						

Table 4: Probability and Stringency of standard revisions

8.2 How taxed boilers standards are updated

To address our second research question, we regress our dependent variables, P_{ijt} and $\Delta Standard_{ijt}$, only for the sample of taxed boilers.[18] The dependent variables are explained as a function of actual emissions for boiler i at time $t-1$, E_{ijt-1}, the availability of NO_x reducing technologies

[18] Another reason for restricting ourself to taxed boilers is that we have information about NO_x emissions only if the boiler is taxed, as the untaxed boilers are not required to report their NO_x emissions to the regulator.

at year $t-1$, and the lagged value of a proxy for "overcompliance" with the standard, measured as the difference between the emissions' concentration specified by the standard and the actual emissions (i.e., $Standard_{ijt} - E_{ijt}$). Our dummy variable overcompliance takes a value equal to one if boiler i overcomplies at a level greater than the median overcompliance of all boilers at year $t-1$. It takes a value equal to zero otherwise. Regarding actual emissions, we consider it as a proxy of cost taxed boilers should optimally reduce emissions up to the point where marginal abatement costs equalize the NO_x tax. Thus, greater abatement of emissions should be expected for low cost type firms than for high cost type firms. Finally, regarding technologies, NO_x is produced largely from an unintended chemical reaction between nitrogen and oxygen in the combustion chamber. The process is quite non-linear in temperature and other parameters of the combustion process, which implies that there is a large scope for NO_x reduction through various technical measures. For example, it is possible to reduce NO_x emissions through investment in post-combustion technologies that clean up NO_x once it has been formed, or through combustion technologies involving the optimal control of combustion parameters to inhibit the formation of thermal and prompt NO_x. Because the adoption of these technologies allows further reductions of NO_x emissions, we expect that their availability increases the probability and stringency of standard revisions. To account for the effect of the availability of NO_x abatement technologies, we include a dummy variable that takes a value equal to one if the boiler had installed NO_x abatement technologies at year time $t-1$, and zero otherwise.

The table below presents the statistics on the three new variable of interest: the overcompliance dummy, NO_x emissions and technology.

Variable	Description	N	Mean	Std.Dev.	Min	Max
Overcompliance$_{t-1}$	1 if overcomplies more than median; 0 otherwise	4275	0.52	0.5	0	1
NO_x Emission$_{t-1}$	mg of NO_x	4605	66.17	29.27	6	250
NO_x Technology$_{t-1}$	1 if NO_x reducing technology; 0 otherwise	7112	0.57	0.50	0	1

Table 5: Statistics on Technology and Compliance by Taxed Boilers

As before, we control for boiler's and firm's characteristics, and sectorial, county and yearly fixed effects. Moreover, we estimate the regressions with robust standard errors clustered at the boiler level. Results are summarized in Table 5 below.

	(1)	(2)	(3)	(4)	(5)	(6)
	P_{ijt}			$\Delta Standard_{ijt}$		
Overcompliance$_{ijt-1}$	0.33^{***}			7.92		
Actual Emissions$_{ijt-1}$		0.002			-0.020	
Technology$_{ijt-1}$			0.17^{**}			-8.66
Log ΔYears$_t$	0.23^{***}	0.29^{***}	0.31^{***}	8.97^{***}	10.08^{***}	10.77^{***}
Size$_{ijt}$	0.000	0.000	0.000	0.011	0.005	0.05^{*}
FE Sector	YES	YES	YES	YES	YES	YES
FE County	YES	YES	YES	YES	YES	YES
FE Year	YES	YES	YES	YES	YES	YES
#Obs	4178	4233	6715	1954	1995	2728
#Boilers	471	472	499	220	221	238
Pseudo R^2/R^2	0.08	0.07	0.07	0.25	0.24	0.28
$^{*}\ p<0.1,^{**}\ p<0.05$ and $^{***}\ p<0.01$						

Table 6: Probability and Stringency of revisions according to over-compliance and cost type

In col (1) we observe that belonging to the group of boilers that over-complies with standards more than the median increases the probability of standard revision. Likewise, in col (3) we observe that having adopted NO_x reducing technologies the previous year also increases the probability of revision. In contrast, in col (2) we observe that the probability of revisions does not seem to be affected by the level of emissions of the boiler (i.e., revisions affecting low and high cost type boilers are equally likely). As before, the number of years that have elapsed since the boiler was last regulated is an important determinant of the probability of revision.

Regarding the stringency of the revisions, the results in cols (4)-(6) show that stringency is not statistically affected by the extent of over-compliance, nor by emissions or the availability of NO_x reducing technologies, but it is significantly affected by the number of years that have elapsed between revisions. We thus obtain no clear empirical pattern on how standards are updated depending on emissions, technology and compliance. However, it is clear that the standards of firms having the best management practices (so they do over-comply with the current level of the standards) are revised more often. As discussed before, a potential explanation of the lack of a significant statistical effect of the NO_x tax on the magnitude of the revisions is that the increased stringency of the standards for taxed boilers spills over, leading to a similar trend of the stringency of the standards of untaxed boilers.

9 Conclusion

Most major environmental problems are addressed by a series of policy instruments enacted at all levels of government, implying that regulations covering the same emission sources overlap and override each other. This paper investigates the informational value of the policy overlap. When one of the instruments in the mix is a market-based instrument incentivizing firms to abate pollution to the cost-minimizing level, information about the firms' abatement costs is revealed and can be used to improve the design of other regulations. Concretely, observing that the firm reduces its emissions beyond what is required by an emission standard, a regulator can conclude that the cost of reducing emissions is lower than expected and can respond by strengthening the standard in the future, to better balance benefits with costs. We characterize the value of such information. To take advantage of the information revealed by the tax, the regulator can relax the standard to obtain a more precise distribution of abatement costs. Although the standard is updated based on the firm's abatement strategy, it always strengthened after the learning phase, regardless of whether the firm overcomplies with the standards. A firm anticipating the future standard update might hide its abatement cost by distorting its abatement effort. This induces a ratchet effect which undermines information revelation. Nevertheless, the tax can still be used to reveal information about abatement costs when the costs are high enough.

Our analysis of the case of the regulation of NO_x emissions by stationary pollution sources in Sweden provides support to our theoretical predictions. We observe that the standards of taxed boilers are revised more often and since, regulators often implement similar standards for similar pollution sources, over time their increased stringency spills over to the stringency of untaxed boilers. The information revealed by the tax thus plays an important role in increasing the overall stringency of regulation of stationary sources of NO_x emissions.

Our paper focuses on the case of a policy mix composed of emission taxes and emission standards. However, the rationale for the informational value of the policy overlap could be easily generalized to the case of other environmental policy mixes where a market-based instrument is used (e.g, interaction of tradable emission permits (TEPs) with other instruments, because TEPs reveal the same type of information about abatement costs as taxes). It could also be generalized to other regulatory policy overlaps. An exampleis the regulation of public utilities, where the regulator often encounters asymmetric information about the cost of production, and the regulation of prices is usually complemented with the regulation of the quality of the products or of pollution, as in Baron (1985). If the costs of improved quality are revealed when the firms make their production decisions, the regulator might be able to infer relevant information about the firms' costs that can be used to better design the quality standards.

A More type revelation with higher tax

Let us consider a tax τ leading to the separating solution s^s with threshold type $\tilde{\theta} = \frac{\tau}{C'(s^s)}$. We show that the threshold type with a higher tax rate is higher: $\tilde{\theta}' = \frac{\tau'}{C'(s')} > \tilde{\theta}$ for any $\tau' > \tau$ where s' is the standard implemented with τ'.

Suppose the reverse. First, we cannot have $\tilde{\theta}' = \tilde{\theta}$ because then $\frac{\tau'}{C'(s')} = \frac{\tau}{C'(s^s)}$, which implies $s' > s^s$ for $\tau' > \tau$. Furthermore, the first-order condition implies $\frac{B'(s')}{C'(s')} = \frac{B'(s^s)}{C'(s^s)}$ which, in turn, implies $s' = s^s$, a contradiction.

Second, suppose now $\tilde{\theta}' < \tilde{\theta}$ and $\tau' > \tau$. Let $\tilde{s}$ be such that $\tilde{\theta} = \frac{\tau'}{C'(\tilde{s})}$. Since s' is the standard implemented by the regulator, this implies that the expected welfare is higher with s' than with $\tilde{s}$, that is:

$$\int_{\underline{\theta}}^{\tilde{\theta}'} W(q^\tau(\theta),\theta)dF(\theta) + \int_{\tilde{\theta}'}^{\bar{\theta}} W(s',\theta)dF(\theta) > \int_{\underline{\theta}}^{\tilde{\theta}} W(q^\tau(\theta),\theta)dF(\theta) + \int_{\tilde{\theta}}^{\bar{\theta}} W(\tilde{s},\theta)dF(\theta)$$

Since $\tilde{\theta}' < \tilde{\theta}$, dividing the above inequality by $1 - F(\tilde{\theta}')$ and using the fact that abatement is at the same level $q^\tau(\theta)$ with both standards s^s and s' for all types $\theta < \tilde{\theta}'$, we obtain:

$$\int_{\tilde{\theta}'}^{\bar{\theta}} W(s',\theta)dF(\theta|\theta \geq \tilde{\theta}') > \int_{\tilde{\theta}'}^{\tilde{\theta}} W(q^\tau(\theta),\theta)dF(\theta|\theta \geq \tilde{\theta}') + \int_{\tilde{\theta}}^{\bar{\theta}} W(\tilde{s},\theta)dF(\theta|\theta \geq \tilde{\theta}') \quad (20)$$

The left-and side of (20) is the expected welfare with s' as a pooling standard over the range $\theta \in [\tilde{\theta}', \bar{\theta}]$ with beliefs $F(\theta|\theta \geq \tilde{\theta}')$ while the right-hand side is the expected welfare with $\tilde{s}$ as a separating standard on the same support with the same beliefs. Inequality (20) tells us that the pooling standard s' dominates the separating standard $\tilde{s}$. The standard s' being pooling implies that the abatement level induced by the tax rate τ for firm $\tilde{\theta}'$ is not higher that the standard, formally $q^{\tau'}(\tilde{\theta}') \leq s'$ with $q^{\tau'}(\tilde{\theta}')$ being defined by $\tau' = \tilde{\theta}'C'(q^{\tau'}(\tilde{\theta}'))$ (see (4)). The last inequality implies $\tilde{\theta}'C'(q^{\tau'}(\tilde{\theta}')) \leq \tilde{\theta}'C'(s')$.

Using $\tau' = \tilde{\theta}'C'(q^{\tau'}(\tilde{\theta}'))$, we obtain:

$$\tau' \leq \tilde{\theta}'C'(s'). \quad (21)$$

On the other hand, since s^s is a separating standard on the support $\theta \in [\tilde{\theta}', \bar{\theta}]$ with beliefs $F(\theta|\theta \geq \tilde{\theta}')$ when the tax rate is τ, we have $q^\tau(\tilde{\theta}') > s^s$, where $q^\tau(\tilde{\theta}')$ is the abatement level induced by the tax τ for the firm of type $\tilde{\theta}'$. The last inequality implies $\tilde{\theta}'C'(q^\tau(\tilde{\theta}')) > \tilde{\theta}'C'(s^s)$. Using $\tau = \tilde{\theta}'C'(q^\tau(\tilde{\theta}'))$, we obtain:

$$\tau > \tilde{\theta}'C'(q^*(\tilde{\theta}')). \quad (22)$$

Using $s' = q^*(\hat{\theta}')$ where $\hat{\theta}' = E[\theta|\theta \geq \tilde{\theta}']$, the two inequalities (21) and (22) imply $\tau' < \tau$, which contradicts our starting assumption. Hence for $\tau' > \tau$, it must hold that $\tilde{\theta}' < \tilde{\theta}$.

B Details and proofs in the dynamic regulation game with myopic firm

B.1 Perfect Bayesian Equilibrium in the dynamic game

A Perfect Bayesian Equilibrium (PBE) of the regulation game with a myopic firm is a set of strategies $s_1, s_2(q_1), q_1(s_1, \theta), q_2(s_2, \theta)$ for $\theta \in [\underline{\theta}, \overline{\theta}]$, and beliefs $f(\theta)$ and $\mu(\theta|q_1)$ for $\theta \in [\underline{\theta}, \overline{\theta}]$ such that:

- $q_t(s_t, \theta)$ minimizes the firm's cost in period t for $t = 1, 2$.
- s_1 maximizes the expected welfare given the beliefs $f(\theta)$.
- $s_2(q_1)$ maximizes the expected welfare given the beliefs $\mu(\theta|q_1)$ for every q_1.
- $\mu(\theta|q_1)$ are updated using Bayes' rule when possible.

Assuming (out-of-equilibrium) passive beliefs, the separating solution is supported by the following strategies and beliefs when $\tau \geq \tau_d$:

$$q_t(s_t, \theta) = \max\{s_t, q^\tau(\theta)\} \text{ for every } \theta \in [\underline{\theta}, \overline{\theta}], t = 1, 2$$

$$s_1 = s_1^d$$

$$s_2(q_1) = \begin{cases} q^*(\theta) & \text{if} \quad q_1 = q^\tau(\theta) \\ s_2^d & \text{if} \quad q_1 = s_1^d \\ s^s & \text{otherwise} \end{cases}$$

$$\mu(\theta|q_1) = \begin{cases} 1 & \text{if} \quad q_1 = q^\tau(\theta) \\ f(\theta|\theta \geq \tilde{\theta}_1) & \text{if} \quad q_1 = s_1^d \\ f(\theta) & \text{otherwise} \end{cases}$$

for all $\theta \in [\underline{\theta}, \bar{\theta}]$, where $\tilde{\theta}_1$ is such that $q^\tau(\tilde{\theta}_1) = s_1$.

B.2 Proof that $\tilde{\theta}_2 = \tilde{\theta}_1$

Suppose the reverse: $\tilde{\theta}_2 \neq \tilde{\theta}_1$. First, we cannot have $\tilde{\theta}_2 < \tilde{\theta}_1$ because $s_2 = q^*(\theta)$ for all types $\theta < \tilde{\theta}_1$ by definition of the separating equilibrium. Second, assume $\tilde{\theta}_2 > \tilde{\theta}_1$. This implies $s_2^d < s_1^d$ by definition of $\tilde{\theta}_T = \dfrac{\tau}{C'(s_t)}$ for $t = 1, 2$. Furthermore, since the second-period expected welfare is higher with s_2^d under any other standard including s_1^d, we have:

$$\int_{\tilde{\theta}_1}^{\tilde{\theta}_2} W(q^\tau(\theta),\theta)dF(\theta|\theta \geq \tilde{\theta}_1) + \int_{\tilde{\theta}_2}^{\bar{\theta}} W(s_2^d,\theta)dF(\theta|\theta \geq \tilde{\theta}_1) > \int_{\tilde{\theta}_1}^{\bar{\theta}} W(s_1^d,\theta)dF(\theta|\theta \geq \tilde{\theta}_1). \quad (23)$$

We show that (23) implies that s_2^d should have been implemented in period 1 rather than s_1^d, which contradicts that s_1^d is the optimal standard in period 1. With s_2^d implemented in both periods, the discounted expected welfare is:

$$\int_{\underline{\theta}}^{\tilde{\theta}_2} \left[W(q^\tau(\theta),\theta) + \beta W(q^*(\theta),\theta)\right] dF(\theta) + [1+\beta] \int_{\tilde{\theta}_2}^{\bar{\theta}} W(s_2^d,\theta)dF(\theta). \quad (24)$$

Since $W(q^*(\theta),\theta) > W(q^\tau(\theta),\theta)$ by definition of $q^*(\theta)$ for every θ, (24) is strictly higher than:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} \left[W(q^\tau(\theta),\theta) + \beta W(q^*(\theta),\theta)\right] dF(\theta) + [1+\beta] \int_{\tilde{\theta}_1}^{\tilde{\theta}_2} W(q^\tau(\theta),\theta)dF(\theta)$$

$$+[1+\beta] \int_{\tilde{\theta}_2}^{\bar{\theta}} W(s_2^d,\theta)dF(\theta). \quad (25)$$

Using (23) multiplied by $1 - F(\tilde{\theta}_1)$ we obtain that (25) is strictly higher than:

$$\int_{\underline{\theta}}^{\tilde{\theta}_1} \left[W(q^\tau(\theta),\theta) + \beta W(q^*(\theta),\theta)\right] dF(\theta) + \int_{\tilde{\theta}_1}^{\bar{\theta}} W(s_1^d,\theta)dF(\theta)$$

$$+\beta \left[\int_{\tilde{\theta}_1}^{\tilde{\theta}_2} W(q^\tau(\theta),\theta)dF(\theta) + \int_{\tilde{\theta}_2}^{\bar{\theta}} W(s_2^d,\theta)dF(\theta)\right], \quad (26)$$

which is the discounted welfare in the separating equilibrium with standard s_1^d in period 1 and s_2^d in period 2. We conclude that (24) is strictly higher than (26): the discounted expected welfare is higher if s_2^d rather than s_1^d is implemented in period 1, a contradiction by definition of s_1^d.

C Details and proofs in the dynamic problem with strategic firm

C.1 Variation of the dynamic incentive-compatibility constraints with θ

Let us write the dynamic incentive-compatible constraint (12) as follow:

$$\theta C(q^\tau(\theta)) - \tau q^\tau(\theta) + \beta[\theta C(q^*(\theta)) - \tau q^*(\theta)] - [\theta C(s_1) - \tau s_1] - \beta[\theta C(q^\tau(\theta)) - \tau q^\tau(\theta)] \leq 0 \quad (27)$$

Differentiating (27) with respect to θ and substituting $\tau = C'(q^\tau(\theta))$, we obtain:

$$\underbrace{C(q^\tau(\theta)) - C(s_1)}_{\text{(a)}} + \beta \underbrace{[C(q^*(\theta)) - C(q^\tau(\theta))]}_{\text{(b)}} + \beta \underbrace{\theta \left[C'(q^*(\theta)) - C'(q^\tau(\theta))\right] \frac{dq^*(\theta)}{d\theta}}_{\text{(c)}}, \quad (28)$$

where $\dfrac{dq^*(\theta)}{d\theta} = \dfrac{C'(q^*(\theta))}{B''(q^*(\theta)) - \theta C''(q^*(\theta))}$ is found by differentiating (2).

Condition (28) decomposes the effects of a marginally higher type θ on the dynamic incentive-compatible constraint of hiding type into three terms. It includes two direct costs: (a) the current cost of hiding type by abating s_1 instead of $q^\tau(\theta)$, (b) the future benefit from hiding type, which is being allowed to abate $q^\tau(\theta)$ units instead of the standard updated at the first-best level $q^*(\theta)$. Both differences are strictly positive because $q^\tau(\theta) > s_1$ and $q^*(\theta) > q^\tau(\theta)$, meaning that the direct effect increases (27) with θ. The remaining term (c) is the indirect effect of a marginally higher type θ: it implies a higher first-best abatement level $q^*(\theta)$ due to a more stringent regulation update if the type is revealed. This indirect effect is negative because $\dfrac{dq^*(\theta)}{d\theta} < 0$. Overall (28) is positive if the direct effect offsets the indirect effect. In this case, the dynamic incentive-compatible constraint from hiding type (12) holds for $\theta < \dot{\theta}$ where $\dot{\theta}$ is defined as the threshold type such that (12) is binding in (13). Hence, the solution separates types lower than θ when (28) is positive, that is under the following assumption.

Assumption 1

$$C(q^\tau(\theta)) - C(s_1) + \beta\left[C(q^*(\theta)) - C(q^\tau(\theta))\right] + \beta\theta\left[C'(q^*(\theta)) - C'(q^\tau(\theta))\right] \frac{dq^*(\theta)}{d\theta} > 0.$$

When Assumption 1 is violated, the dynamic incentive-compatible constraint from hiding type (12) never holds and, hence, the solution is pooling.

To see under which conditions Assumption 1 holds, let us write the right-hand side of

(28) as follows:

$$-\beta \frac{\left[C'(q^*(\theta)) - C'(q^\tau(\theta))\right] C'(q^*(\theta))}{\dfrac{B''(q^*(\theta))}{\theta} - C''(q^*(\theta))}. \tag{29}$$

Condition (28) is positive when (29) is small compared to the other terms in (28). That is, (i) when $C(q)$ is not "too convex" because then $C'(q^*(\theta))$ is close to $C'(q^\tau(\theta))$ and $C''(.)$ is low and positive so that the denominator is high, (ii) $B''(.)$ is high, meaning that B is "very concave" (or the damage from pollution is "very convex", implying that the marginal damage from pollution is increasing substantially with pollution concentration), (iii) β is low so that the present extra cost of hiding dominates the future gain.

C.2 Proof of Proposition 3

In the definition of $\tilde{\beta}(\theta)$ in (15), let $N(\theta) \equiv \theta C(q^\tau(x)) - \tau q^\tau(x) - [\theta C(q^\tau(\theta)) - \tau q^\tau(\theta)]$ denote the numerator and $D(\theta) \equiv \theta C(q^*(\theta) - \tau q^*(\theta) - [\theta C(q^*(x)) - \tau q^*(x)]$ the denominator. Since $x > \theta$, we have $\dfrac{dN(\theta)}{d\tau} = q^\tau(\theta) - q^\tau(x) > 0$ and $\dfrac{dD(\theta)}{d\tau} = q^*(x) - q^*(\theta) < 0$. Therefore, since $N > 0$ and $D > 0$, we conclude:

$$\frac{\tilde{\beta}(\theta)}{d\tau} = \frac{\dfrac{dN(\theta)}{d\tau} D - N \dfrac{dD(\theta)}{d\tau}}{D^2} > 0,$$

for all $\theta > x$.

Differentiating (13) leads to:

$$\frac{d\dot{\theta}}{d\tau} = \frac{q^\tau(\dot{\theta}) - q^\tau(\tilde{\theta}_1) + \beta[q^*(\dot{\theta}) - q^\tau(\dot{\theta})]}{C(q^\tau(\dot{\theta}) - C(q^\tau(\tilde{\theta}_1)) + \beta[C(q^*(\dot{\theta}) - C(q^\tau(\dot{\theta})] + \beta[\dot{\theta} C'(q^*(\dot{\theta}) - \tau] \dfrac{dq^*(\dot{\theta})}{d\dot{\theta}}}. \tag{30}$$

The numerator in (30) is positive because $\dot{\theta} > \tilde{\theta}_1$ so that $q^\tau(\dot{\theta}) < q^\tau(\tilde{\theta}_1)$. The denominator is also positive under Assumption 1.

D Details and proofs in the two-types case

D.1 Perfect Bayesian Equilibrium with two types

A Perfect Bayesian Equilibrium (PBE) of the (two-periods) regulation game with two types (and myopic firm) is a set of strategies $s_1, s_2(q_1), q_1(s_1, \theta), q_2(s_2, \theta)$ for $\theta = \underline{\theta}, \overline{\theta}$, and beliefs ν_1, $\nu_2(\theta|q_1)$ for $\theta = \underline{\theta}, \overline{\theta}$ such that:

- $q_t(s_t, \theta)$ minimizes the firm's cost in period t for $t = 1, 2$

- s_1 maximizes the expected welfare given the beliefs ν_1
- $s_2(q_1)$ maximizes the expected welfare given the beliefs $\mu_2(q_1)$ for every q_1
- $\nu_2(q_1)$ are updated using Bayes' rule when possible.

Assuming (out-of-equilibrium) passive beliefs, the separating solution is supported by the following strategies and beliefs when $\tau \geq \tau_d$:

$$q_t(s_t,\theta) = \max\{s_t, q^\tau(\theta)\} \text{for } \theta = \underline{\theta}, \overline{\theta}, t = 1, 2$$

$$s_1 = \overline{q}^*$$

$$s_2(q_1) = \begin{cases} \overline{q}^* & \text{if} \quad q_1 = s_1 \\ \underline{q}^* & \text{if} \quad q_1 = q^\tau(\theta) \\ \hat{q}^* & \text{otherwise} \end{cases}$$

$$\nu_2(\underline{\theta}|q_1) = \begin{cases} 1 & \text{if} \quad q_1 = \underline{q}^\tau \\ 0 & \text{if} \quad q_1 = s_1 \\ \nu_1 & \text{otherwise} \end{cases}$$

and $\nu_2(\overline{\theta}|q_1) = 1 - \nu_2(\underline{\theta}|q_1)$. The pooling solution is supported by the following strategies and believes when $\tau \leq \tau_d$:

$$q_t(s_t,\theta) = \max\{s_2, q^\tau(\theta)\} \text{ for } \theta = \underline{\theta}, \overline{\theta}, t = 1, 2$$

$$s_1 = s_2(q_1) = \hat{q}^* \text{ for all } q_1$$

$$\nu_2(\underline{\theta}|q_1) = \nu_1 \text{ for all } \ q_1$$

and $\nu_2(\overline{\theta}|q_1) = 1 - \nu_2(\underline{\theta}|q_1) = 1 - \nu_1$.

D.2 Proof that τ_s is the minimal tax for the separating solution

First we show that $\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu)W(\overline{q}^*, \overline{\theta}) > W(\hat{q}^*, \hat{\theta})$ when $\tau > \tau_s$ and $\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu)W(\overline{q}^*, \overline{\theta}) < W(\hat{q}^*, \hat{\theta})$ when $\tau < \tau_s$. To show that, first observe that $\underline{q}^\tau$ increases with τ while $\overline{q}^*$ and $\hat{q}^*$ do not change with τ. Therefore the left-hand side of (16) is increasing with τ while the right-hand side does not change when τ varies. Second, for a low tax rate such that $\underline{q}^\tau \approx \overline{q}^*$, we have $\nu W(\underline{q}^\tau, \underline{\theta}) + (1-\nu)W(\overline{q}^*, \overline{\theta}) \approx E_\theta[W(\overline{q}^*, \theta)] < W(\hat{q}^*, \hat{\theta})$, where the last inequality is due to the definition of $\hat{q}^*$ that maximizes $E_\theta[W(q,\theta)]$ with respect to q. Therefore, the left-hand side of (16) is lower than the right-hand side. The reverse holds when the tax is increased up to $\underline{q}^\tau = \hat{q}^*$ because $W(\underline{q}^\tau, \underline{\theta}) = W(\hat{q}, \hat{\theta})$ while $W(\overline{q}^*, \overline{\theta}) = W(\hat{q}, \hat{\theta})$ by definition of $\overline{q}^*$.

Next we show that the separating solution is incentive-compatible when $\tau \geq \tau_s$, i.e. $\underline{q}^{\tau} > s = \overline{q}^*$ if $\tau \geq \tau_s$. Suppose that the reverse holds: $\underline{q}^{\tau} < \overline{q}^*$ while $\tau \geq \tau_s$. Then $W(\underline{q}^{\tau}, \underline{\theta}) \leq W(\overline{q}^*, \underline{\theta})$ because $\underline{q}^{\tau} \leq \overline{q}^* < \underline{q}^*$, which implies $\nu W(\underline{q}^{\tau}, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) \leq \nu W(\overline{q}^*, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) = W(\overline{q}^*, \hat{\theta}) < W(\hat{q}^*, \hat{\theta})$ where the last inequality is due to the definition of $\hat{q}^*$. This contradicts $\nu W(\underline{q}^{\tau}, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) \geq W(\hat{q}^*, \hat{\theta})$ when $\tau \geq \tau_s$.

Second, we show that the pooling solution is incentive-compatible when $\tau \leq \tau_s$, i.e. $q(\underline{\theta}) = \hat{q}^* < \underline{q}^{\tau}$ if $\tau \leq \tau_s$. Suppose that the reverse holds: $\underline{q}^{\tau} > \hat{q}^*$ while $\tau \leq \tau_s$. Then $W(\underline{q}^*, \underline{\theta}) > W(\hat{q}^*, \underline{\theta})$ because $\underline{q}^* \geq \underline{q}^{\tau} > \hat{q}^*$. Furthermore, since $W(\overline{q}^*, \overline{\theta}) > W(\hat{q}^*, \overline{\theta})$, it implies $\nu W(\overline{q}^*, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) > E_{\theta}\left[W(\hat{q}^*, \hat{\theta}\right] = W(\hat{q}^*, \hat{\theta})$, which contradicts $\nu W(\underline{q}^{\tau}, \underline{\theta}) + (1-\nu) W(\overline{q}^*, \overline{\theta}) \leq W(\hat{q}^*, \hat{\theta})$ when $\tau \leq \tau_s$.

References

Ahlvik, L. and M. Liski (2017) Carbon leakage: a mechanism design approach, working paper

Baron, D.P. (1985) Regulation of price and pollution under incomplete information, *Journal of Public Economics*, 28:211-231.

Bennear, L.S. and Stavins, R.N. (2007) Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics 37*: 111-129.

Caillaud, B. and G. Demange (2017) Joint Design of Emission Tax and Trading Systems, *Annals of Economics and Statistics* 127: 163-201.

Coria, J., M. Hennlock and T. Sterner (2018) Fiscal Federalism, Interjurisdictional Externalities and Overlapping Policies, Working paper, Department of Economics, University of Gothenburg.

Dasgupta, P., P. Hammond, and E. Maskin (1980) On Imperfect Information and Optimal Pollution Control, *Review of Economic Studies*, 67: 857-860.

Duggan, J. and J. Roberts (2002) Implementing the Efficient Allocation of Pollution, *American Economic Review* 92(4):1070-1078.

Fankhauser, S., Hepburn, C. and Park, J. (2010) Combining multiple climate policy instruments: how not to do it. *Climate Change Economics 1*: 209-225.

Freixas, X., R. Guesnerie and J. Tirole (1985) Planning under incomplete information and the ratchet effect *The Review of Economic Studies* 52(2): 173-191.

Mandell, S. (2008) Optimal mix of emissions taxes and cap-and-trade. *Journal of Environmental Economics and Management*, 56:131-140.

Novan, K. (2017) Overlapping environmental policies and the impact on pollution. *Journal of the Association of Environmental and Resource Economists 4*: 153-199.

Laffont, J.J. and J. Tirole, (1988) The dynamic of incentive constracts. *Econometrica* 56(5): 1153-1175.

Lecuyer, O. and P. Quirion (2013) Can uncertainty justify overlapping policy instruments to mitigate emissions?. *Ecological Economics 93*: 177-191.

Lehmann, P. (2012) Justifying a policy mix for pollution control: a review of economic literature. *Journal of Economic Surveys 26* 71-97.

Levinson, A. (2011) Belts and suspenders: Interactions among climate policy regulations, in *The Design and Implementation of US Climate Policy* (pp. 127-140). University of Chicago Press.

Lewis, T. (1996) Protecting the environment when costs and benefits are privately known, *RAND Journal of Economics* 27(4): 819-847.

Martimort, D. and W. Sand-Zantman (2016) A Mechanism Design Approach To Climate-Change Agreements, *Journal of the European Economic Association* 14(3): 669-718.

Phaneuf, D. and T. Requate (2017) *A Course in Environmental Economics: Theory, Policy, and Practice*, Cambridge University Press

Pizer, W.A. (2002) Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics* 85: 409-434.

Roberts, M.J. and M. Spence (1976) Effluent charges and licenses under uncertainty. *Journal of Public Economics* 5: 193-208.

Spulber, D.F. (1988) Optimal environmental regulation. *Journal of Public Economics* 35: 163-181.

Weitzman, M. (1974) Prices vs. Quantities. *Review of Economic Studies* XLI: 477-449.